

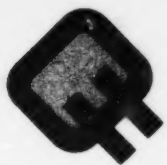
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EROSION OF CLAY-BASED GROUTS IN
SIMULATED ROCK FRACTURES

Report No 86-271-K

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ABSTRACT

The report presents a laboratory study on the erosion of clay-based grouts in a simulated rock fracture and in a simulated rock fracture network model. The apparatus specially constructed for these experiments and the testing procedure are described. The testing results have shown that a partially eroded clay-based grout can still be effective, although to a lesser degree, in sealing rock fractures and that the addition of cement in a clay grout can minimize erosion.

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EROSION OF CLAY-BASED GROUTS IN SIMULATED ROCK FRACTURES

H.T. Chan

1.0 INTRODUCTION

Previous laboratory studies on clay grouts have indicated that a clay grouting material can be very impermeable, ie, values of hydraulic conductivity ranging from 10^{-8} m/s to 10^{-10} m/s/l/. Therefore, it can be concluded that if a clay grout is injected into rock fractures and the integrity of the grout is maintained, the flow rate of water through the grouted rock mass should be very small. However, if some of the grouting material is eroded by the percolating water, the flow rate of water through the grouted rock mass would significantly increase. To study this concern, it was decided to investigate the erosion problem of clay-based grouts in simulated rock fractures in the laboratory, and to get some indications of the reduction in the effectiveness of grouting due to partial erosion of the material in fractures.

In this report, the experimental program, the apparatus specially designed and constructed for the grout effectiveness study and the testing procedure will be described. Also, the experimental data will be discussed and conclusions will be drawn.

2.0 GROUT EROSION IN SIMULATED ROCK FRACTURE NETWORK

Tests were performed to simulate the groundwater flow conditions in a small block of fractured rock immediately adjacent to a shaft (Figure 1). It may be assumed that some years after the backfill is placed in the shaft, recharging groundwater in the host rock will flow towards the compacted backfill.

A small block of rock as shown in Figure 1 would be subjected to groundwater seepage under a large hydraulic gradient from B to A. If the fractures in the host rock are grouted, the grouting material would then be subjected to potential erosion due to the percolating groundwater. The erosion of the grouting material in the sub-horizontal direction may create a critical flow path in the vertical upward direction for the movement of radio-nuclides in the groundwater.

To simulate the fractures in a block of rock, an interlocking plastic cube (47.6 mm x 47.6 mm x 50 mm) was constructed using Lego blocks (Figure 2). This simulated a fracture network consisting of three mutually perpendicular smooth cracks. Because the water flow direction in a laboratory test was always vertical, the cube had to be oriented in a certain direction during a test. The sides of the cube were given letter designations for identification purposes. The thickness of the rock fractures was controlled by the thickness of the brass shims glued on the surfaces of the interlocking plastic pieces. The "grouting" of the fractures was achieved by dipping the individual Lego blocks in the grout mix and then interlocking them together to form a cube. Excessive grout was wiped off from the surface of the cube before testing.

The fractured cube was set up in a triaxial cell in the manner similar to that of setting up a soil sample in the cell (Figures 3 and 4)/2/.

Square porous stones were placed on the top and bottom sides of the cube to distribute the water pressure. A double membrane with "O" rings on both sides were used to seal the sides of the cube. A protective rubber sleeve was placed over the cube. The corners of the cube were bevelled so that they would not cut into the rubber when it was in the triaxial cell. A cell pressure of 360 kPa was used to seal the sides of the cube and to tighten the Lego blocks so that no water would permeate between the sides of the cube and the membrane. A double burette system was used to measure both the inflow and outflow from the cube.

Initially, the flow rates of the fractured cube without grout were measured from face "B" to face "A" and then from face "D" to face "C". Then, two more sets of tests were performed with pure bentonite or bentonite-cement grout being used separately in sealing the fractures in the cube.

For the "erosion" test, the water flow was from face "B" to face "A" and the applied water pressure was up to 100 kPa. The nominal hydraulic gradient from face "B" to face "A" of the cube

was therefore about 200. The flow rate was monitored during the experiment and the test was terminated when the flow rate through the cube became fairly constant.

After the "erosion" test, the cube was removed from the triaxial cell. The cube was then turned 90° and again was set up in the cell. This time, the water flow was in the direction from face "C" to face "D" of the cube. A smaller water pressure (ie, 25 kPa) was used in the flow test because the purpose of the test was not on the erosion of the grout in the fractures but on measuring the rate at which water could move through the partially eroded grout.

Table 1 summarizes the data on the flow rate measurements of the ungrouted fractured cube and on the cube grouted either with bentonite or with bentonite-cement material. Comments on the significance of each test and its results are also included in the table.

By comparing the flow rates of water through the fractured cube for the following conditions: (i) when the fractures were not grouted; (ii) when the fractures were grouted; and (iii) when the grout in the fractures was partially eroded, it was possible to estimate the consequence of erosion of the grouting material and hence the effectiveness of the grout in sealing the fractures.

3.0 GROUT EROSION IN A SINGLE FRACTURE

The experimental study described in the previous section has demonstrated the problem associated with erosion in the use of clays as a grouting material in rock fractures. Furthermore, the test results have shown that the addition of cement in a clay material can minimize erosion.

In these water seepage tests, however, it was not possible to see the movement and performance of the grout in the fractures. Therefore, another apparatus was designed and constructed to further study the behaviour of several grout mixes and the factors affecting grout erosion in a single simulated rock fracture.

The rock fracture was simulated by a gap formed by two plates. In the initial design, the top plate was a 38 mm thick plexi-glass, 610 mm long by 216 mm wide. The bottom plate was 13 mm thick aluminum, also 610 mm long by 216 mm wide. A transparent top plate was used so that the position of the grouting material in the simulated rock fracture could be seen. Figures 5 and 6

show the details of the plates put together to form the gap, the thickness of which was determined by the thickness of small brass shims placed in a grid between the plates. A valve and pressure gauge were connected to the "injection port" and the grout was injected through this opening with an injecting device (Figure 7). After the grouting material was injected into the gap, the "injection port" was shut off. Water through the "inflow port" was then allowed to percolate through the grouting material in the gap under pressure and the water was collected through the "outflow port" and the volume measured by a burette.

During the course of the experimental program, the design of the apparatus was improved. The improved model consisted of the same plexiglass plate and a stainless steel plate of the same dimensions as in the previous design. Because a chemical reaction between the brass gasket shim and the aluminum plate was noted in the preliminary tests, the brass gasket was replaced with a 3 mm diameter rubber gasket. A groove 1.5 mm deep was milled into the plexiglass top plate 25 mm in from the edges all around the plate. This groove accepted the new rubber gasket and was 3 mm in width. Another change in design was to install a porous stone to spread the percolating water from the "inflow port." The five steel bars placed across the plates were used to reduce the deflection of the plates under pressure. The modified apparatus can be used for injection, hydraulic conductivity and erosion tests.

In order to simulate a fracture in granite, another model was also designed with two pieces of granite slabs. The dimensions of the slabs were 254 mm x 98 mm x 35 mm. The rough surface of the granite was used to form one face of the simulated fracture (Figures 8 and 9).

In the granite model, it was not possible to see the grout in the fracture through the upper rock slab. Various ways for determining the position of the grouting material within the slabs were considered. Finally, the "light sensor" technique was evolved. Basically, an infrared light emitter, inserted in the upper granite slab, was used to transmit light and the intensity was measured by means of a light detector located in the lower slab. The intensity of the light detected would vary according to the amount of grout present between the detector and the emitter. An infrared light source was used because of its constant light intensity. The light intensity was measured by a voltmeter and a decrease in light intensity was indicated by an increase in the measured voltage. The holes were drilled into the rock with masonry bits of 12.7 mm and 4.8 mm on a drill press with water squirted onto the bit as a coolant. The 1.6 mm glass window holes were drilled with a diamond dust dental bit.

A number of tests were carried out in the simulated rock fracture formed by the two smooth plates. Generally, a small pressure (eg, several kPa) would be sufficient to inject the selected grout into a fracture of 0.25 mm or 0.50 mm thickness. The grout would not fill up completely the fracture between the plates so that during an "erosion" test, the grout could move in the remaining un-grouted fracture space. Usually, a small water pressure (< 100 kPa) was used to determine the hydraulic conductivity (k) of the injected grout. Then the water pressure would be increased in steps and would be maintained for several days to several weeks. The behaviour of the grout, such as the development of channels within the grouting material, could be inspected through the transparent plate and photographed if desired.

Several types of clay-based grouting materials were used in this experimental program:

- (1) Sodium bentonite and water.
- (2) Sodium bentonite, cement and water.
- (3) Calcium bentonite, cement and water.
- (4) Calcium bentonite, cement, silica fume and water.

In Table 2, the data pertinent to each test with the grouting material in the simulated fracture formed by two smooth plates are summarized.

Only one test was done using the simulated fracture formed by the two granite slabs. The objective of this experiment was to find out how well the "light sensor" technique could be used to map the location of the grouting material within the fracture. A grout mix of 4 parts of water and 1 part of sodium bentonite was used for this test. The grout was injected in a fracture of 1.8 mm (average) thickness using an injecting pressure of 5 kPa. The distribution pattern of the grout within the fracture was mapped using the point data obtained by the light sensors. Then the rock slabs were opened up and the actual grout distribution pattern could be seen and compared with that inferred by the light sensors. It has found that the inferred grout distribution pattern was quite similar to the actual distribution.

4.0 SUMMARY

In this laboratory study, apparatus were designed and constructed and testing procedures were proposed for the investigation of the erosion of clay-based grouting materials in a simulated rock fracture network and in a simulated rock fracture. The

testing equipment and procedure will be useful for the evaluation of the grouting materials to be used for sealing the rock fractures in an underground repository for radioactive fuel wastes.

With the available apparatus, laboratory tests were carried out to study the factors affecting the erosion potential of several clay-based grouts. A number of observations have been obtained from these tests.

- (1) Erosion of clay grouts (eg, bentonite and water) may be minimized or avoided if the hydraulic pressure acting on the grout is not greater than the grout injecting pressure. Also, if the clay-grout is completely confined, erosion of grout would not be a concern.
- (2) The addition of cement or cement/silica fume in a clay can increase the strength of a clay-based grout and hence decrease its erosion potential. Naturally, the optimum proportioning of the various grout components depends on their individual properties. Laboratory tests similar to those carried out in this study will be useful in designing the grout mixes.
- (3) Since the pure clay grouts and clay grouts with cementitious additives possess different characteristics in terms of hydraulic conductivity, erosion potential, strength, and injectability in fractures, it would be beneficial to use two different types of grouting materials in sealing rock fractures. Again, a laboratory study can be made on the sealing performance of the two different grouts injected in a simulated fracture, as demonstrated by one of these tests performed in the single simulated rock fracture.

ACKNOWLEDGEMENTS

Messrs. Bob Rankin and Bob Dowdell of the Civil Research Department in Ontario Hydro Research Division provided valuable assistance in the laboratory testing program and their contributions are gratefully acknowledged. Funding for this study was partially provided by the Nuclear Materials Management Department in Ontario Hydro.

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2. BISHOP, Alan W., and D.J. Henkel, "The Measurement of Soil Properties in the Triaxial Test", Edward Arnold (publishers) Ltd., London, 1962.

TABLE 1: SUMMARY OF TEST RESULTS ON THE FRACTURED CUBE.
THE FRACTURES WERE 0.13 MM WIDE

Grout Mix	Flow Direction	Applied Pressure P (kPa)	Q, Flow Rate (mL/min)	$\frac{Q}{P}$	Comments
No grout in fractures	B to A	10	8.8	8.8×10^{-1}	Test done to establish the value of Q/P from Face "B" to Face "A" of the fractured cube without grout. The hydraulic gradient was about 20 for P = 10 kPa.
	C to D	10	8.4	8.4×10^{-1}	Test done to establish the value of Q/P from Face "C" to Face "D" of the fractured cube without grout. Q/P values similar for tests from B to A and from C to D.
3 parts of water + 1 part Na Bentonite by weight	B to A	25	1.5×10^{-6}	6.0×10^{-8}	Fractured cube sealed with bentonite grout. The Q/P value was decreased by about 10^7 times, which shows the effectiveness of the clay grout. Test lasted 9 days.
	B to A	100	5.8×10^{-5}	5.8×10^{-7}	The value of Q/P is still small. The increase of Q/P from 6.0×10^{-8} to 5.8×10^{-7} was probably due to some movement of the grout. Test lasted 17 days.
	C to D	25	1.8×10^{-2}	7.2×10^{-4}	Large increase of the Q/P value was due to erosion and movement of the grout in the fractures (10^{-7} to 10^{-4}). However, the Q/P value is still about 10^3 times smaller than the Q/P value for the ungrouted cube (ie, grouting is still effective to a certain extent).
3 parts of water + 1 part of Na Bentonite and cement by weight (Bentonite: cement=3:1)	B to A	25	2.7×10^{-4}	1.1×10^{-5}	The bentonite/cement mix was "cured" for 7 days before the flow test. The value of Q/P for this grout was much larger than that of bentonite. The increase was probably due to the addition of cement in bentonite. Test lasted 30 days.
	B to A	100	2.3×10^{-3}	2.3×10^{-5}	Test lasted 20 days.
	C to D	25	4.1×10^{-3}	1.6×10^{-4}	Increase in the Q/P value from 10^{-5} to 10^{-4} due to erosion and movement of the grout in fractures. The increase was about 10 times compared with about 10^3 times for pure bentonite, because cement was added to the bentonite and the grout strength was increased. The bentonite/cement grout was useful in sealing the fractures (Q/P decreased from $\approx 10^{-1}$ to $\approx 10^{-4}$). Test lasted 15 days.

TABLE 2: SUMMARY OF RESULTS FROM GROUT EROSION TESTS
IN SINGLE SIMULATED ROCK FRACTURE
FORMED BY TWO SMOOTH PLATES

Grout Mix	Gap Thickness (mm) 1	Average Length of Grout Specimen, L (mm) 2	Maximum Injection Pressure (kpsi) 3	Applied Water Pressure P (kpsi) 4	Hydraulic Gradient (1) 5	Duration (Days) 6	Equivalent k_h (m/s) 7	Comments
4 parts of water 1 part of Avonite (No) Bentonite (By weight)	0.25	255	10	5 10 20 30 45 70 90 200	2 4 8 12 18 26 36 80	3 5 5 23 42 9 60 41	- 8.7×10^{-10} 9.0×10^{-10} 8.9×10^{-10} 5.1×10^{-10} 5.1×10^{-10} 4.4×10^{-10} 9.9×10^{-6}	-Grout taking on water. -Grout was effective at ΔP 9 times of max injecting pressure. -Channeling in grout. k_h value greatly increased.
4 parts of water 1 part of Avonite (No) Bentonite	0.25	50	150	750	1530	80	8.6×10^{-11}	-The grout plug was retained by the filter stone at one end and a strip of #54 Whatman Filter Paper at the other end (i.e. the grout was completely confined). -Some unconnected fine cracks perpendicular to the direction of water flow appeared 14 days after test, but they were closed up 42 days after their appearance.
16 parts of water, 3 parts of Avonite Bentonite, 1 part of Type 10 cement	0.25	280	5	50	18	3	2.3×10^{-7}	-Grout specimen cured for 7 days before the flow test. -Injection easier for this grout than for bentonite grout. - k_h value much larger than that of bentonite grout (10^{-7} vs 10^{-10}). It appeared that the addition of cement to bentonite caused the grouting material to form larger "aggregates." -No channeling in grout when the applied water pressure was 10 times of the injecting pressure.
16 parts of water, 3 parts of Avonite Bentonite, 1 part of Type 10 cement	0.25	220	3	50 100 150 200 250 300	23 46 70 93 116 139	20 7 14 10 26 6	5.9×10^{-8} 6.7×10^{-8} 1.2×10^{-7} 3.0×10^{-7} 1.8×10^{-6} 2.1×10^{-6}	-Grout specimen cured for 7 days before the flow test. -Some fine channels developed in the grout. k_h value increased.
16 parts of water, 3 parts of Avonite Bentonite, 1 part of Type 10 cement	0.25	220	3	50 100 200 300	23 46 93 139	14 9 8 41	1.8×10^{-6} 2.8×10^{-6} 7.5×10^{-6} 2.1×10^{-6}	-Grout specimen cured for 7 days before the flow test. -Grout mix same as the above specimens. Initial k_h value much larger because the grout was not filling the gap as well as the above specimens.
7 parts of water, 4 parts of Pumilio (Ca) Bentonite, 1 part of cement	0.50	155	10	100 200 250	66 132 198	15 8 165	2.8×10^{-8} 1.8×10^{-8} 2.4×10^{-3}	-Grout specimen cured for 7 days before the flow test. -Channels in grout visible. k_h value greatly increased.
7 parts of water, 4 parts of Pumilio (Ca) Bentonite, 1 part of cement	0.50	220	10	100 200 250 300	44 88 116 139	1 25 12 4	3.3×10^{-8} 1.3×10^{-8} 2.8×10^{-7} 3.7×10^{-7}	-Grout specimen cured for 7 days before the flow test. -Some channels appeared in the grout but they were not inter-connected.
7 parts of water, 4 parts of Pumilio (Ca) Bentonite, 1 part of cement	0.25	113	10	50 150 200 250 300	44 133 177 222 266	7 14 6 4 31	4.2×10^{-9} 2.4×10^{-8} 5.3×10^{-8} 8.0×10^{-8} 3.8×10^{-7}	-Grout specimen cured for 7 days before the flow test. -Some small channels developed by erosion or movement of particles but they were not inter-connected. k_h value increased.
35 parts of water 20 parts of Pumilio (Ca) Bentonite, 4 parts of cement, 1 part of silica fume	0.50	175	50	100 200 250 300 350 400 450 500 700	58 116 145 174 203 233 262 291 407	5 3 5 11 8 7 1 2 4	3.9×10^{-9} 3.1×10^{-9} 2.8×10^{-9} 2.6×10^{-9} 2.6×10^{-9} 2.5×10^{-9} 2.3×10^{-9} 2.3×10^{-9} 2.3×10^{-8}	-No visible channels.
35 parts of water 20 parts of Pumilio (Ca) Bentonite, 4 parts of cement, 1 part of silica fume (Plug "A")	0.50	175	50	50 100 150 200 250 300 350 400 500 600	13 27 41 55 69 83 96 110 137 165	1 1 0.1 6 9 4 5 2 5 1	2.3×10^{-8} 2.4×10^{-8} 2.3×10^{-8} 8.9×10^{-9} 5.3×10^{-9} 5.3×10^{-9} 5.3×10^{-9} 4.3×10^{-9} 5.3×10^{-9} 3.1×10^{-9} 4.1×10^{-9} 8.1×10^{-7} 1.0×10^{-6}	-Plug "A" was injected first followed by Plug "B" and there was some mixing or blending at the boundary of the plugs. Plug "A" provided confinement to Plug "B" (clay and water grout). -At $\Delta P=600$ kpa, Plug "A" could still confine Plug "B". The k_h value of the composite grout was small. -Channeling through sample.
4 parts of water 1 part of Avonite (No) Bentonite (Plug "B")	193	50		350 400 500 600	96 110 137 165	4 2 5 1	5.3×10^{-9} 4.3×10^{-9} 5.3×10^{-9} 3.1×10^{-9}	

1. Thickness of gap between 2 smooth plates.
2. Length of grout specimen injected in the gap by a cartridge injecting pressure.
3. Maximum pressure used for injection.
4. Water pressure used to force water through the grout specimen. Pressure was increased in steps.
5. Hydraulic gradient i = Applied water pressure/Average length of grout specimen.
6. Number of days the water pressure was applied to the grout specimen.
7. Equivalent hydraulic conductivity (k_h) is equal to:

$$k_h = \frac{Q}{A \cdot i} \quad Q = \text{flow rate through the specimen, } i = \text{hydraulic gradient, } A = \text{cross-sectional area of grout specimen perpendicular to flow direction.}$$

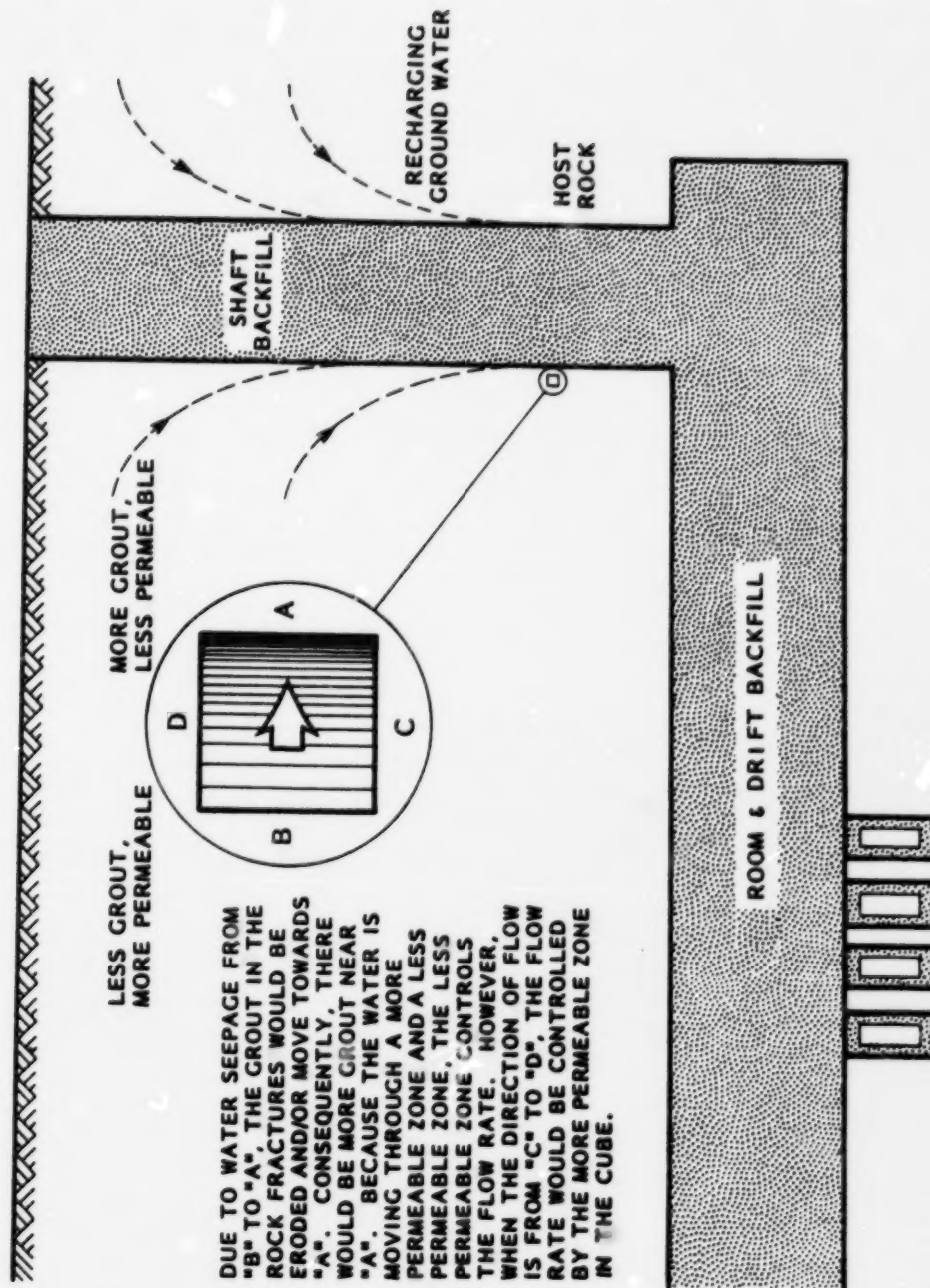


FIGURE 1
GROUND WATER FLOW CONDITIONS IN A SMALL BLOCK OF ROCK
IMMEDIATELY ADJACENT TO A VERTICAL SHAFT

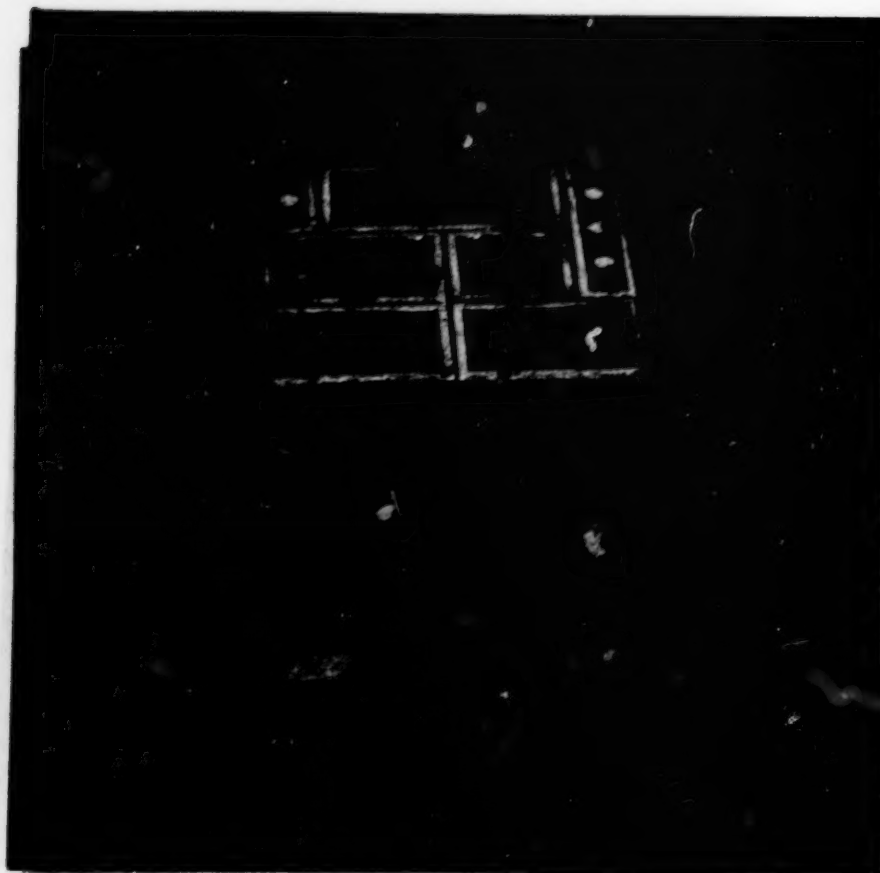


FIGURE 2
INTERLOCKING PLASTIC CUBE CONSTRUCTED WITH LEGO BLOCKS.
THE HOLLOW SPACE WITHIN A LEGO BLOCK WAS FILLED WITH WAX
(CUBE DIMENSIONS 47.6mm X 47.6mm X 50mm)

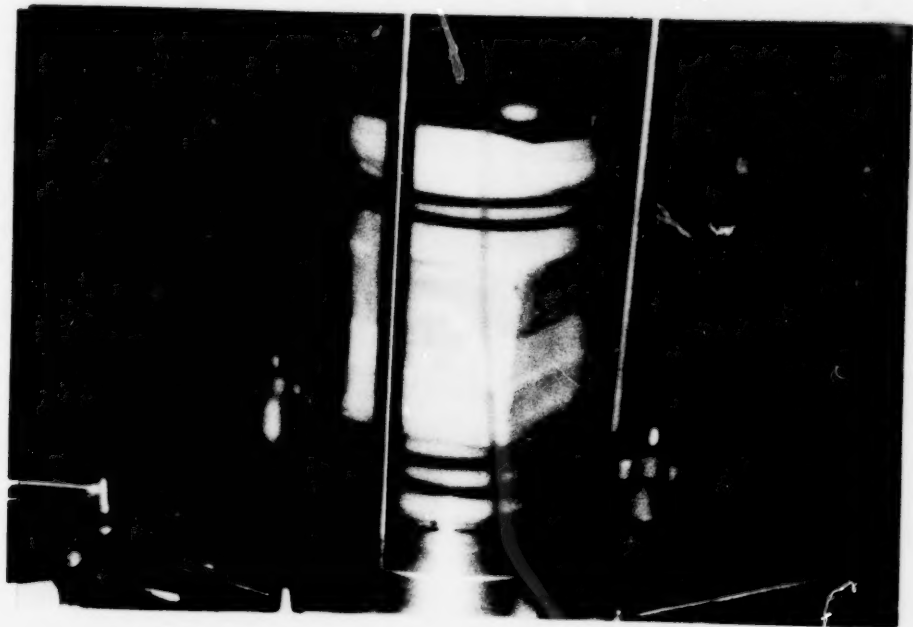


FIGURE 3
THE FRACTURED CUBE IN A CONVENTIONAL TRIAXIAL CELL

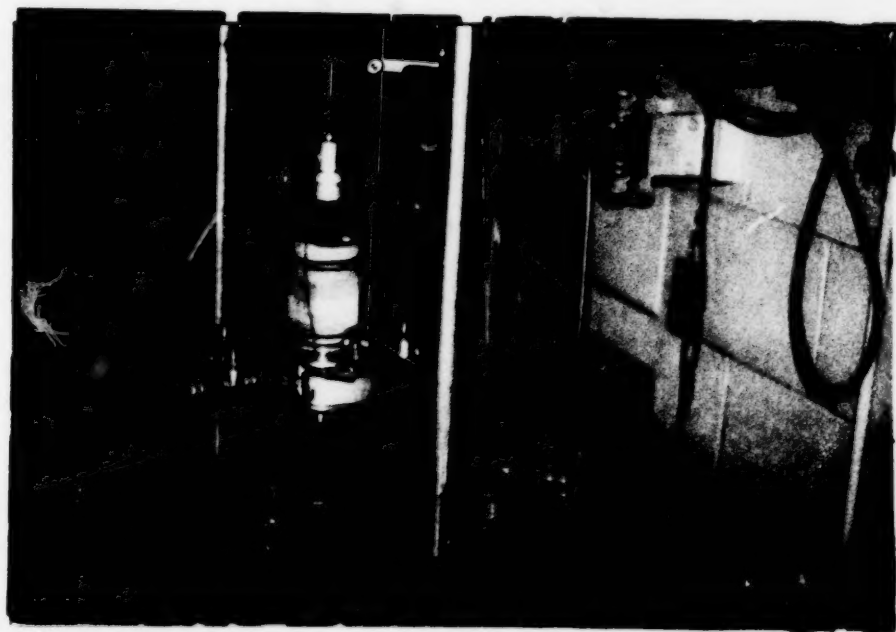
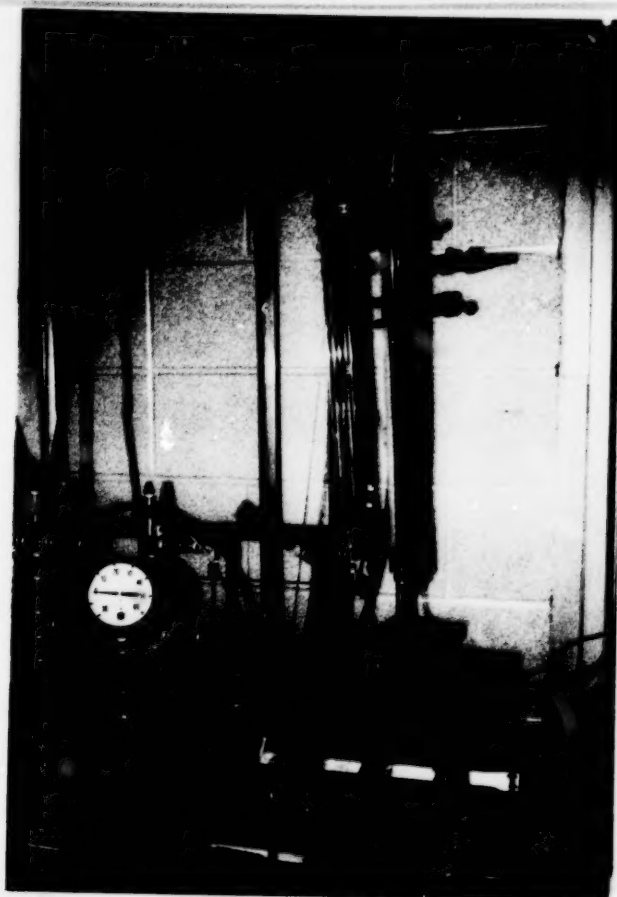
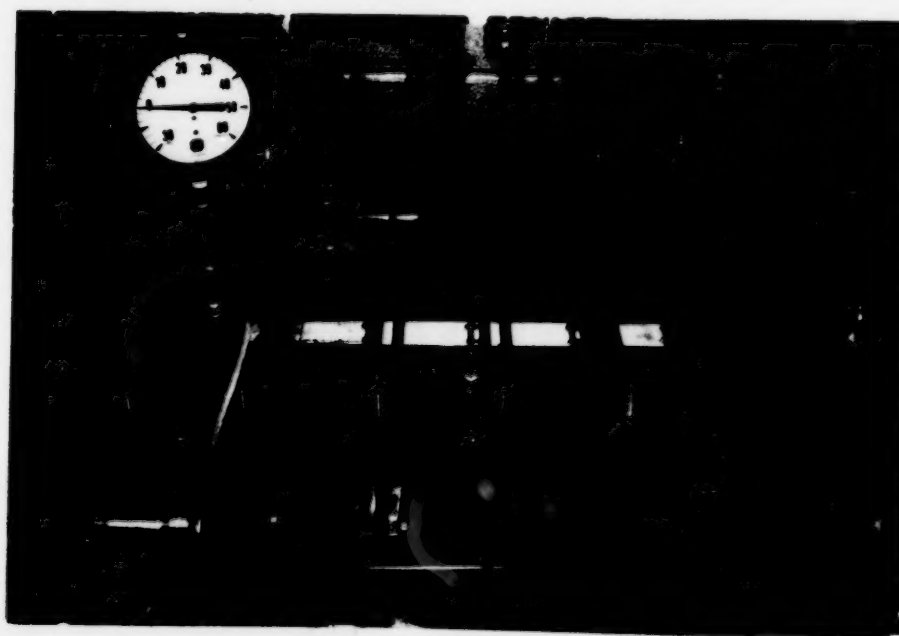


FIGURE 4
TRIAXIAL SYSTEM USED TO MEASURE THE
FLOW THROUGH THE FRACTURED CUBE



(a) Distant View



(b) Close-up View

FIGURE 5
A SIMULATED ROCK FRACTURE MODEL
FORMED BY TWO SMOOTH PLATES

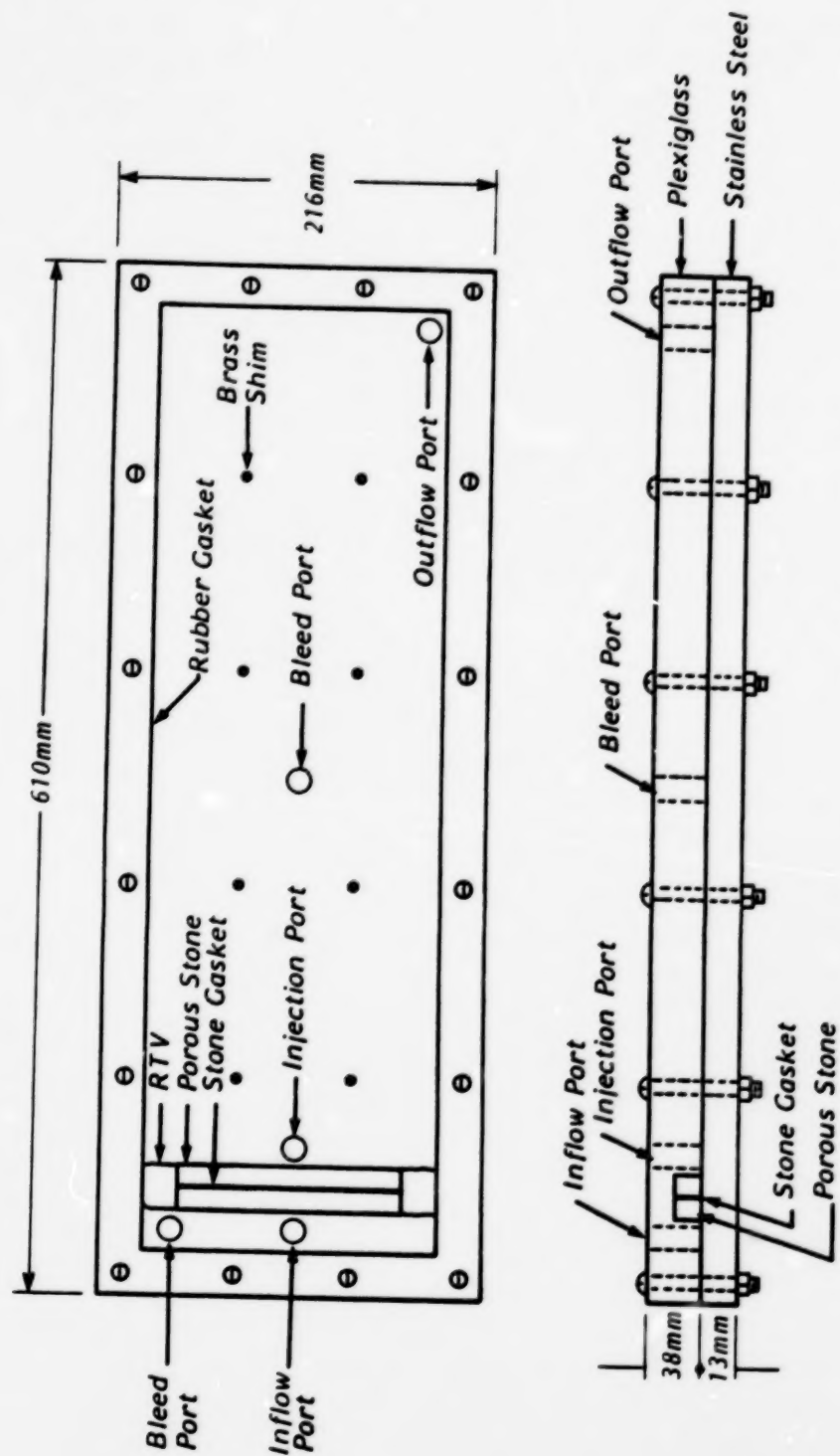
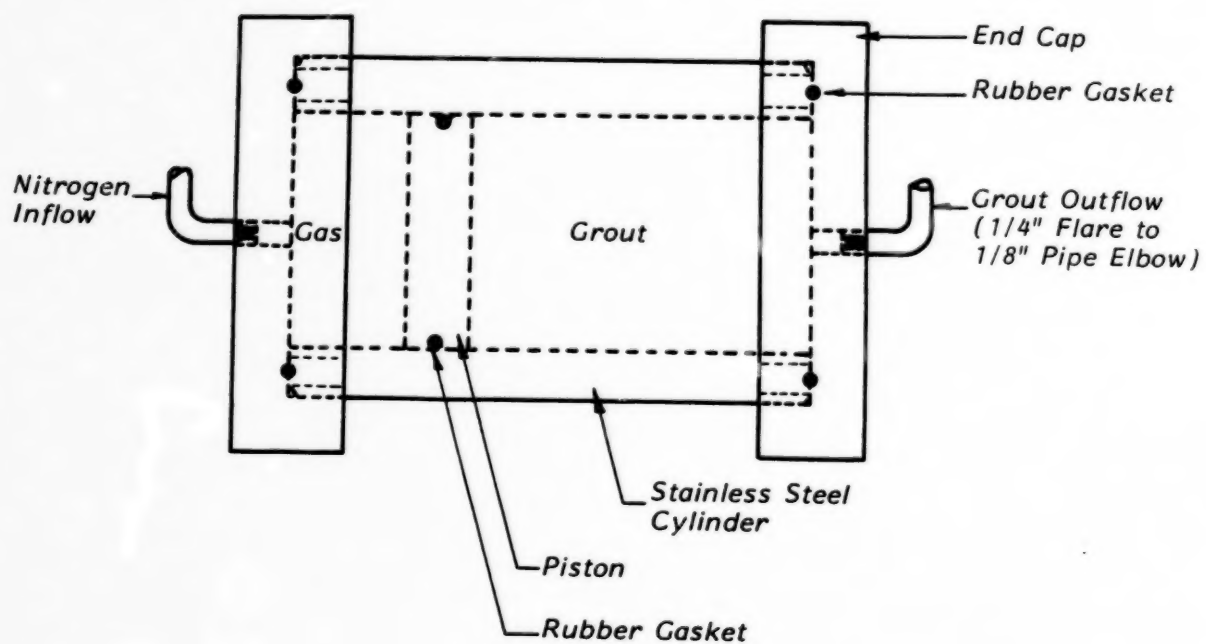


FIGURE 6
DETAILS OF THE SINGLE-FRACTURED MODEL



(Drawing to Scale)

FIGURE 7
GROUT INJECTING DEVICE



FIGURE 8
SINGLE FRACTURE MODEL
FORMED BY TWO GRANITE SLABS

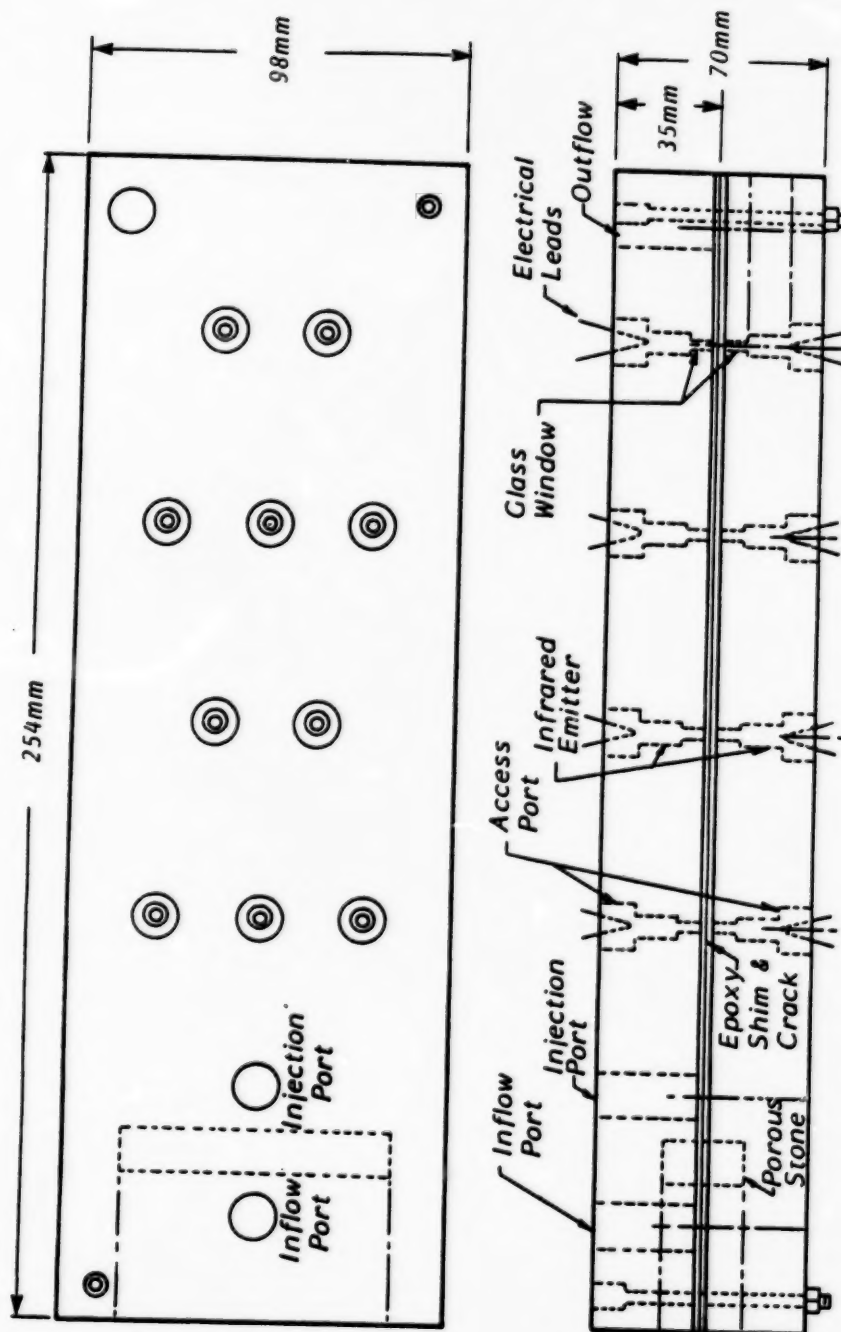


FIGURE 9
DETAILS OF THE GRANITE MODEL